II. CLOSED-CYCLE MAGNETOGASDYNAMIC POWER GENERATION

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One application of the research at Lewis Research Center in plasma physics is in the field of direct energy conversion, specifically in the field of magnetohydrodynamic power generation. The principles of operation of these generators are reviewed first. Figure II-1 shows a magnetic field in the vertical direction, a conductor in the horizontal direction, and electrodes attached to the sides of the conductor. When the conductor moves perpendicular to the magnetic field, a voltage is induced whose direction is perpendicular to both the direction of the magnetic field and the direction of velocity of the conductor. If an electrical circuit with a load is completed between the electrodes, then electrical power is generated. This principle does not change if the conductor is a solid, a liquid, or a gas. When a liquid or a gas is used, then the generator is usually called a magnetohydrodynamic (MHD) generator, although "magnetogasdynamic" is preferable for generators that use gaseous conductors.

MHD power generation offers several advantages. In thermodynamic cycle turboalternator systems, thermal energy is transferred to a gas or vapor at a high pressure. This fluid is then expanded to a low pressure in a turbine. If one could utilize the expanding fluid itself as a conductor, then the need for rotating machinery could be eliminated. The stresses in static equipment are less than in rotating machinery. Since material strength decreases with temperature, the lower stress requirements make it possible to use fluids at much higher temperatures. This aspect makes an MHD generator a candidate for space application as well as for high efficiency ground-based systems. Also, MHD offers the possibility of very large generator power levels because the principle of induced voltage involves body (or volume) forces rather than surface forces such as turbines. MHD systems may be simpler than turboalternator systems because of the lack of seals, bearings, and other auxiliary equipment associated with rotating machinery. For an MHD system it is necessary to have only a moving conductor in a magnetic field.

TYPES OF GENERATORS

Figure II-2 shows the schematic of a closed thermodynamic cycle MHD generator system. The magnetic field is applied in the generator volume. The velocity is obtained by heating a gas to a high temperature at a high pressure and then expanding the gas to a low pressure and high velocity. The kinetic energy is then taken from the fluid by the generator, and the fluid is cooled, compressed, and heated for a return through the generator. In an open cycle system, the fluid does not return to the compressor but is exhausted to the environment. However, the fluids that can be easily accelerated - namely, the gases and the vapors - do not have high conductivity at temperatures below 2500 K and pressures above 1 atmosphere. Two approaches have been suggested to get around this problem. One approach, suggested by Dave Elliott of JPL, is to transfer the kinetic energy of the expanded gas with low conductivity to a liquid metal with a high conductivity. This technique has problems that are mainly ones of fluid mechanical interraction and induction generator design. Although this approach may be promising in space, it is not discussed in the paper since there is no element of plasma physics involved. The other approach to solving the low conductivity problem is to raise the conductivity of the gas. This can be achieved by heating the electrons to 2500 K. Here again the attempts are divided into two groups as shown in table II-1. One group raises the temperature of the gas to heat the electrons and obtain high equilibrium conductivity, and the other group tries to raise the temperature of the electrons only and obtain a high nonequilibrium conductivity. These two groups can be characterized by the difference in the method of providing the high temperature fluid.

Open Thermodynamic Cycle

If the energy is provided as a result of a chemical or nuclear reaction in the gas itself, then temperatures above the melting point of solids can be used if adequate cooling is provided for any solids exposed to these hot gases. Presently the high temperature is provided by the combustion of liquid fuels in either oxygen or preheated air. The systems are open cycle, and the combustion products are released into the atmosphere. The temperatures attainable this way are sufficient to provide adequate conductivity if potassium, or some other easily ionizable seed, is added. Figure II-3 shows one such unit. This generator, built by the Avco-Everett Research Laboratory in Boston, Massachusetts, has delivered 31.3 megawatts for a period of about 1 minute. The burner is to the left and the magnetic field on the right. The fuel is alcohol burning in oxygen. Other generating units

are constructed in Japan and the Soviet Union. The applications for these generators include a topping cycle for a central station power plant, an emergency or peaking generator to be used on an intermittent basis, or any application involving a large amount of power for a short time.

These open cycle units have operated for periods up to 50 hours using liquid fuel. The present development in this field is directed toward coal combustion. Programs to develop long life electrodes and insulators as well as seed material recovery systems are under way. There is also some evidence that operation at high power densities may involve a fluid mechanical problem called generator "stall" where boundary layer separation occurs. The limits on this phenomenon must be studied. Because of the ground-based application of these generators, research and development has been sponsored by private industry and to some extent by the Department of Defense. Many problems associated with these equilibrium generators are quite different from the nonequilibrium generators.

Closed Thermodynamic Cycle

Consider an alternate method of providing the high temperature gas. If the energy is to be transferred to the gas from hot solid surfaces, such as a solid core reactor, the gas temperature is limited to temperatures below 2500 K where the equilibrium conductivity (at pressures necessary for efficient energy conversion) is too low. This problem may not exist in case of liquid or gas core reactors, and it may be possible to utilize equilibrium conductivities in a closed cycle with these reactors. However, to use gas MHD generators with solid core reactors some form of nonequilibrium conductivity (e.g., using electric fields) must be found. The effort at Lewis is directed toward studying the feasibility of nonequilibrium conductivity generators for use in space in conjunction with a solid core nuclear reactor. (Fig. II-4 is an isometric drawing of the Lewis MHD generator.) Research groups in Russia, Germany, and Italy, as well as the United States, are also concerned with this problem. In the United States, the other groups are located at MIT, G.E., and AVCO.

GENERATOR CURRENT-VOLTAGE CHARACTERISTICS

Figure II-5 gives a schematic fiew of an MHD generator. The working fluid enters the generator from the left, and the magnetic field direction is into the plane of the figure. As the fluid passes through the generator the ions move toward the top

and the electrons toward the bottom. This charge separation creates an electric field E_F in the positive direction, for the coordinate system chosen. At the same time there is a tendency for the electrons to be slowed down by the magnetic field. This tendency is larger for greater values of the Hall parameter. The ions, on the other hand, are coupled more strongly to the neutrals and are less affected by the magnetic field. This phenomenon also gives rise to a charge separation, with the ions tending to migrate to the downstream end of the generator. This charge separation also creates an electric field E_H, called the Hall field, in a direction opposite to the velocity. If electrical circuits are provided for currents in the induced field or Faraday direction j_F and in the Hall direction j_H (which have resistances denoted by R_F and R_H, respectively), then the currents and fields in the generator can be controlled because of their dependence on the circuit resistances. This dependence can be calculated by using Ohm's law for the external circuitry and the variation of Ohm's law, which is appropriate for the gas resistance inside the generator. The vector representation of this Ohm's law, along with the vector diagram representing solutions to this equation, is shown in figure II-6. This Ohm's law was discussed in the paper by Seikel et al. The vectors $\sigma\vec{u} \times \vec{B}$, $\sigma\vec{E}_F$, and $\sigma\vec{E}_H$ are shown in figure II-5. The result of these vectors is the vector $\sigma(\vec{E} + \vec{u} \times \vec{B})$, and from the form of the Ohm's law, the two terms that add up to this vector must be at right angles to each other. Therefore, the locus of points of the current vector must lie on a semicircle as shown in the figure. It is evident how the direction of the current and electric fields can change depending on the Hall parameter and the induced voltage. It is possible to use Ohm's law for the generator and the external circuitry to solve for the currents and voltages inside the generator as a function of the induced voltage, the Hall parameter, and the magnitudes of the external resistances.

ELECTRON HEATING

As a result of the current flowing inside the generator, energy is added to the electrons proportional to the scalar product of the current and the effective electric field. This energy is called joule heating. In order for the electrons to maintain a steady-state energy level, they must, in turn, get rid of this energy; this is done by collisions with the neutrals and ions. The amount of energy delivered to the heavy particles is porportional to the difference between the electron temperature and the heavy particle temperature. The proportionality constant depends on the particular heavy particle involved in the collision. If internal energy levels can be excited, then larger amounts of energy can be transferred in the collision. This is the situation, for example, when diatomic and polyatomic molecules are present.

For this reason, the largest temperature difference is obtained when atoms are used. The important parameters governing the behavior of the joule heating are the Hall parameter, the type of atoms, and the ratios of the external circuit resistance to the internal generator resistance. These ratios are denoted by ρ_x and ρ_y for the Hall and Faraday directions, respectively.

Figure II-7 shows the amount of electron temperature elevation over the gas atom and ion temperature as a function of the Hall parameter. The Faraday resistance ratio is taken as one which would represent maximum power generation for a generator with constant internal impedance. There are several curves that correspond to different values of the resistance in the Hall direction ρ_x, which goes from 0 to ∞. At values of 0 and ∞ the names Faraday Continuous and Faraday Segmented have been applied, respectively. It is noted, first of all, that as the Hall parameter increases, the electron temperature increases. Second, for a given Hall parameter, the electron temperature increases with increasing Hall resistance ratio. This is the concept being studied to provide a nonequilibrium conductivity in the generator. As the electron temperature increases, the number of electrons increases and, hence, the conductivity is elevated.

The elevation in electron temperature is greatest at open circuit in the Hall direction, because this corresponds to the largest Hall electric field. There is a twofold advantage here: First, an $\vec{E}\times\vec{B}$ drift velocity is added to the $\vec{u}\times\vec{B}$ drift velocity, thereby enhancing the current; and second, as a result of the increased current, there is increased electron heating and a consequent electron temperature rise. The temperature elevation depends quite critically on the ability to prevent the Hall currents from flowing.

This nonequilibrium process is, of course, not new. It is the situation in any discharge tube. The only difference is the use of the induced voltage resulting from the motion of the conductor through the magnetic field as the driving voltage. Experimental verification of this result has been obtained with a magnetic field for both a stationary gas with an applied voltage and a flowing gas with an induced voltage. The largest effect in the latter case has been obtained by using MHD generators operating in shock tubes.

EFFECT OF FLUCTUATIONS

As mentioned previously, any Hall current decreases the amount of electron heating, primarily because of the reduction in the Hall electric field. John Smith in the previous paper discussed the effects of fluctuating components of the Hall current and the fact that they also can reduce the Hall voltage. In that sense, then,

fluctuations and Hall leakage have the same effect. A comparison between these two effects is shown in figure II-8. The effective Hall parameter, which is defined as the ratio of the Hall field to the difference between the induced and Faraday field, is plotted as a function of the Hall parameter. As before, the Faraday resistance ratio is 1.0. The ideal curves represent the effect of leakage resistance. With infinite resistance, the effective Hall parameter equals the Hall parameter. As the leakage resistance decreases, so does the effective Hall parameter. At a resistance ratio of 10 the effective Hall parameter is below 2.0. Also shown in this figure is the curve considering instabilities with no Hall leakage for the case of cesium-seeded argon at 2000 K and a Mach number of 0.5. Notice that for this situation the effective Hall parameter is also below 2.0. These calculations are based on an instability model developed by Dr. Albert Solbes of MIT. He shows that this model agrees well with some observed experimental evidence. This curve indicates that resistance ratios must be around 100 or greater in order to be limited only by the instabilities.

As mentioned previously, there is quite a difference between the amount of nonequilibrium conductivity obtained in the shock tube and that obtained in steady-flow generators. This difference may be related to our experience with the MPD thrusters. At high power levels and short times, as discussed by Charles Michels, two differences are observed: the discharge becomes more "resistor-like" and less "arc-like", and there is no rotating spoke. It is possible that both differences can be explained by the short time period which may be too short for instabilities to develop into a full fledged fluctuation, or turbulence. This short time period may also prevent the development of current shorting paths that are found in the longer time generators.

Effect of Impurities

Now a generator is considered with a large resistance ratio, and the effect of carbon monoxide impurities is examined. These impurities lower the electron temperature and ultimately the power output. Figure II-9 shows the effect of both fluctuations and the impurities on the power density of an MHD generator with no Hall leakage. Conditions in this figure are the same as in the previous one, except that the magnetic field strength is fixed at 1.0 tesla and the load parameter varied from open circuit to short circuit. Curve e is considered first. This curve shows the equilibrium conductivity, which is the conductivity given by the gas conditions and not a function of the joule heating or of the load parameter. This equilibrium conductivity provides a power density of about 0.3 megawatt per cubic meter at a

load parameter corresponding to a Faraday resistance ratio of 1. For the ideal curve (no impurities and no instabilities), two things may be observed. The power density is increased by about a factor of 20, and the peak shifts to regions of lower load parameter. Curve b illustrates the effect of instabilities above load parameters of about 0.2. The power density drops off rather rapidly. Curve c, which considers the effect of impurities only, shows the power density with the addition of 1000 ppm of carbon monoxide. The effects of other diatomic impurities are roughly the same as for carbon monoxide. The maximum power density is reduced to about 15 times the equilibrium value, and its value is below that of the ideal case and that of the instability case (for load parameters below 0.38). Curve d shows the effect of both impurities and instabilities. The peak is shifted even further toward short circuit, and the maximum is only about a factor of 3 greater than equilibrium. Also, for load parameters above 0.5, the curve lies below the equilibrium curve. As a result of this calculation it seems that the impurity level must be kept well below the value of 1000 ppm. It should be mentioned that the effect of both instabilities and impurities can be lessened by using a supersonic Mach number.

As a result of these studies performed at Lewis, it seems reasonable to require resistance ratios in the Hall direction to be in the hundreds and impurities to be below 1000 ppm (and perhaps as low as 100 ppm). Fluctuation are probably going to exist, so they must be included in any performance analysis.

SPACE POWER SYSTEM STUDY

In order to determine the operating parameters to be used in the experimental program, a system study of a possible MHD system for use in space is considered. In this study it is important to include the efficiency of such generators. Figure II-10 shows the isentropic efficiency of an ideal MHD generator designed for minimum volume and operating with an outlet to inlet pressure ratio of 0.5 as a function of load parameter. Note that the efficiency is higher at larger values of the load parameter. This is in conflict with the power density requirement which indicates higher power density at low values of the load parameter. In space, the dictates of generator efficiency must be respected since the reactor and shielding weight will probably be the dominant weight of any space power system. Notice also that, for a given generator efficiency, as the Mach number increases so must the load parameter, which, in turn, tends to lower the power output. This is an effect that tends to offset many of the advantages of supersonic Mach number as far as nonequilibrium effects are concerned.

The results of the system study are now examined. The generator for the

system is assumed to be operating as part of a Brayton cycle. The working fluid is neon, the cesium seed fraction is 0.003, the Mach number is 2.0, the generator pressure ratio is 0.5, and the length is 0.5 meter. These specifications correspond to approximately a 1-megawatt generator at 10 atmospheres. The efficiency and radiator area are chosen such that these values equaled corresponding values for a potassium turbine with an inlet temperature of 2000° F (1365 K). The instability analysis of Solbes is used to account for fluctuations. Figure II-11 shows the results of this study where the magnetic field strength is plotted on the ordinate as a function of the maximum cycle temperature with pressure as a parameter. The temperature range spans the regions from 1500 K, which is approximately the limit for turbines, to 2500 K, which is approximately the value for which equilibrium conductivity is sufficient for MHD systems. Consider the point at 2000 K and 10 tesla. The required pressure is then seen to be 10 atmospheres. This point represents a possible system operating point. The pressure is sufficiently high to provide adequate reactor heat transfer. The magnetic field strength is within the present day state of the art. The temperature of the working fluid is approximately the same as that achieved for the nuclear rocket program. However, the temperature is probably the most difficult value to achieve for long time periods. Notice the effects if operation is attempted at a lower temperature. If the magnetic field strength is kept constant, then the pressure decreases and reactor heat transfer will suffer. On the other hand, if the pressure is kept constant, then the magnetic field requirements increase and may be larger than available superconducting materials can provide. It seems reasonable, therefore, to try to develop an MHD generator to operate at 2000 K, which is therefore the temperature chosen for our experiment. The Hall parameter for this condition is about 12 and the effective Hall parameter is about 0.36. For the experiment both the magnetic field strength and the system pressure have been lowered by a factor of 5, while still maintaining the Hall parameter value of 12. Of course, the power density is decreased, but the feasibility of the technique of nonequilibrium ionization can still be studied. The facility uses argon, has a graphite resistance heater, and is capable of operating to at least a 2100 K maximum temperature.

LEWIS EXPERIMENTAL RESULTS

The first item to consider is the amount of impurities in the facility. Because of the graphite resistance heater, hydrogen and carbon monoxide impurities are released. It has been possible to maintain the level of these impurities down to about 500 ppm with a purge flow which removes the impurities at their generation rate.

We have taken precautions to provide as high a value as possible of the wall resistance in the Hall and Faraday directions. Figure II-12 shows the present test section. The gas flow is into the figure. The outer stainless steel supporting structure and the insulating bricks can be seen. Ceramic keys are used to hold the bricks in place, and the electrodes are not touching the surfaces, so that any cesium on the surface will not provide a shorting path. All insulating surfaces exposed to the cesium are coated with a higher purity aluminum oxide in an attempt to reduce any chemical reaction with cesium. The cesium injection tube is at the entrance. It is now possible to maintain resistance to ground at around 2 kilohms, even after cesium has been injected. However, the possibility that during the time of injection the cesium does lower this resistance cannot be eliminated.

We feel that this resistance is about as high as it can be for the wall temperatures being used. Therefore, a further increase in the resistance ratio must be made by reducing the internal generator resistance (especially if the value of leakage resistance decreases with the injection of cesium). It is possible to cool the walls, but this procedure does not seem compatible with an efficient generator, unless, of course, it is a very large generator. Also, at a lower temperature, the effect of cesium deposit on the walls may even be enhanced.

There is another reason for trying to reduce the generator resistance. The joule heating of the electrons can occur only when the current flows, and since generators are inherently voltage generators, the current can flow only when the internal impedance is low. Therefore, some means must be used to create ions to provide the conductivity to get the procedure started. This is called preionization because it occurs before the gas enters the generator. Therefore, the solution to the preionization problem may also hold the solution to the excessive leakage problem.

In some of our recent tests, the possibility has been investigated of applying a voltage to successive electrode pairs of the generator as a method of preionization. If the effective discharge resistance decreases for successive electrode pairs, then the preionization is successful. In figure II-13(a) the effective discharge resistance is plotted as a function of seed fraction for three successive electrode pairs. The magnetic field strength is about 1.0 tesla. The effective discharge resistance, or the generator resistance, decreases when going from electrode pair 3 to 4 to 5. The resistance increases, if anything, with seed fractions above 0.1 percent. At a seed fraction of 0, the effective discharge resistance becomes very large.

Figure II-13(b) shows the effect of the magnetic field strength on the generator resistance. Again the effective resistance is plotted for three successive electrode pairs. The resistances are plotted as a function of the magnetic field strength for a

seed fraction of about 0.05 percent. Successive discharges do apparently reduce the discharge resistance. Also, the resistance increases with increasing magnetic field strength for all electrode pairs. At the highest magnetic field strength the discharge became unstable and the current, rather than going directly across the channel, shorted along the channel and passed through one of the load circuits downstream.

The encouraging feature of the data shown by these two slides is that after sufficient preionizing the discharge resistance is reduced below 20 ohms. If the leakage resistance can be held above 2000 ohms, then a resistance ratio of above 100 can be maintained. This condition is necessary for the attainment of non-equilibrium ionization. Hopefully, further reduction in the discharge region is possible with more preionization.

In our future research, we plan to concentrate on the preionization of the plasma. It is this area which holds the most promise for developing elevated electron temperatures. We would like to study the means of controlling the cathode sheath drop and the mode of electrode emission. We will also try to reduce those factors which tend to hinder the achievement of electron heating. One possibility is to operate with a supersonic generator. This seems to provide a larger region of load parameter where detrimental effects of impurities and instabilities can be reduced. There is also the possibility of operating with a different geometry. There are, for example, generators made with diagonal conducting walls along the equipotential surfaces of the generator. There is some evidence that the performance is better for this geometry. A very attractive feature of these generators is that the number of load circuits can be reduced to one, rather than equal to the number of electrode pairs as in the Faraday generator. Finally, it may be of interest to raise the magnetic field strength and the pressure to generate larger amounts of power. This will require the use of superconducting magnets. Another advantage of these magnets is the possibility of increased access to the test section for diagnostic equipment and instrumentation.

The goal of our research is to determine the lowest maximum cycle temperature for which one can still achieve reasonably good performance with an MHD generator.

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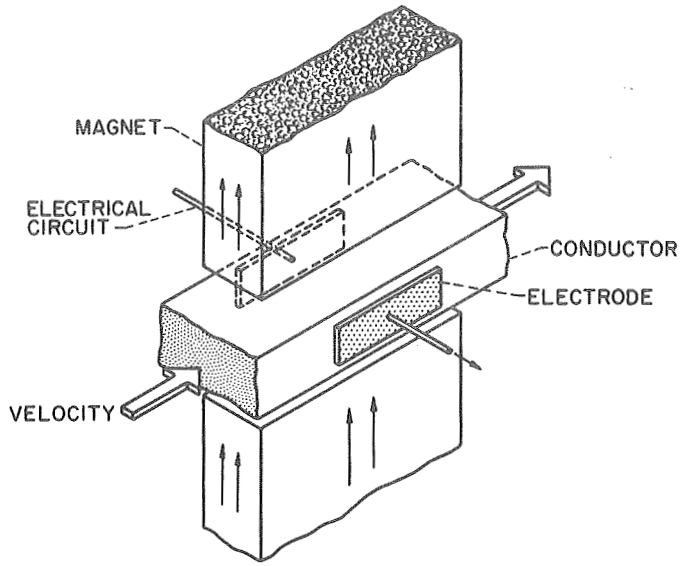
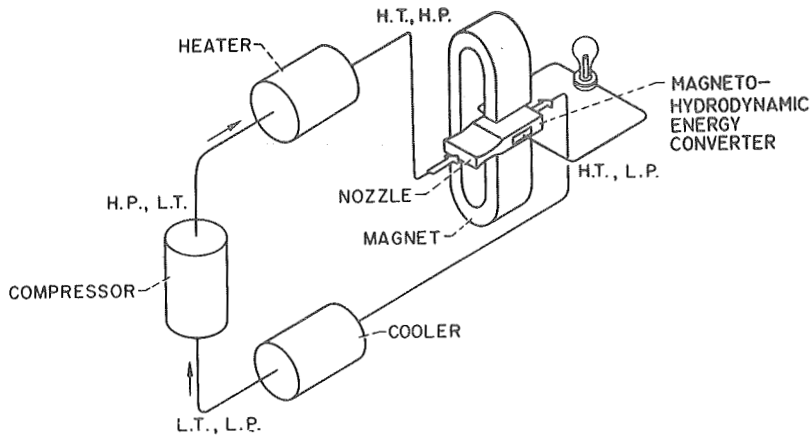
TABLE II-1. - HIGH GAS CONDUCTIVITY

Method of heating gas	Gas temperature, K	Method of heating electrons	Thermodynamic cycle
Heat exchanger	<2500	Electric fields	Closed
Chemical or nuclear reaction	>2500	Collisions	Open



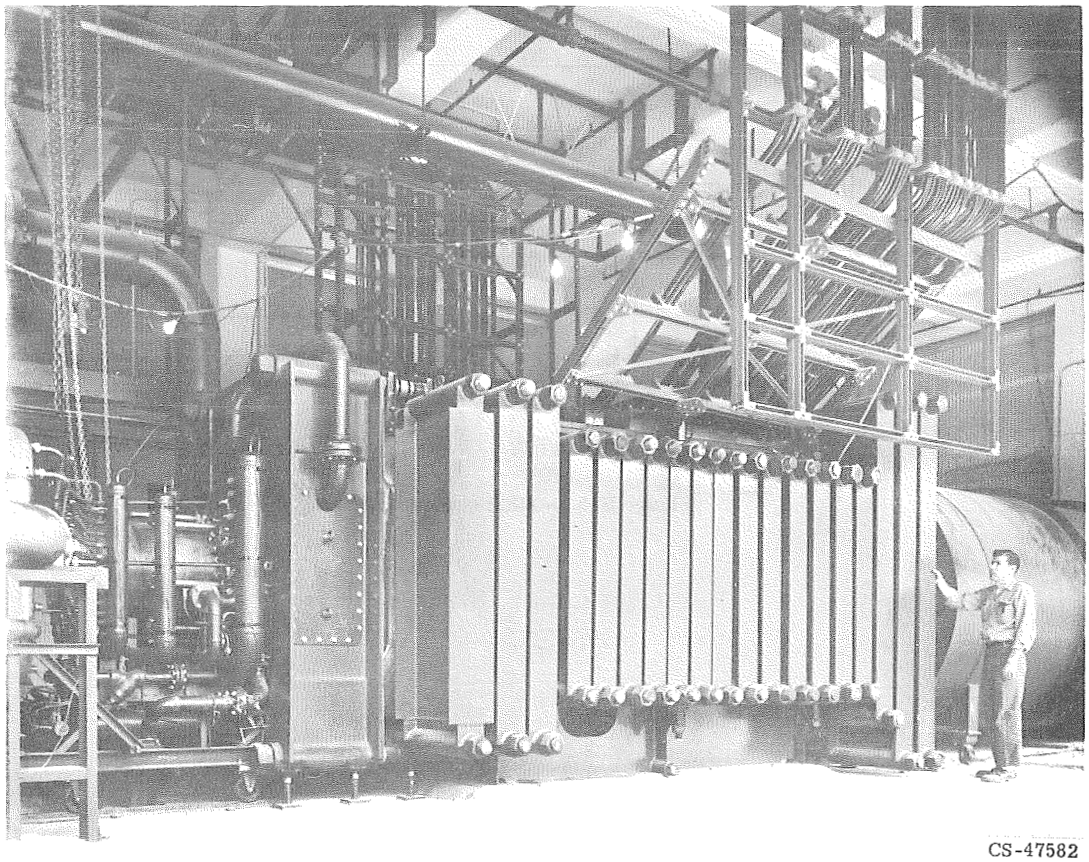
CS-26152

Figure II-1. - Conductor moving in magnetic field.



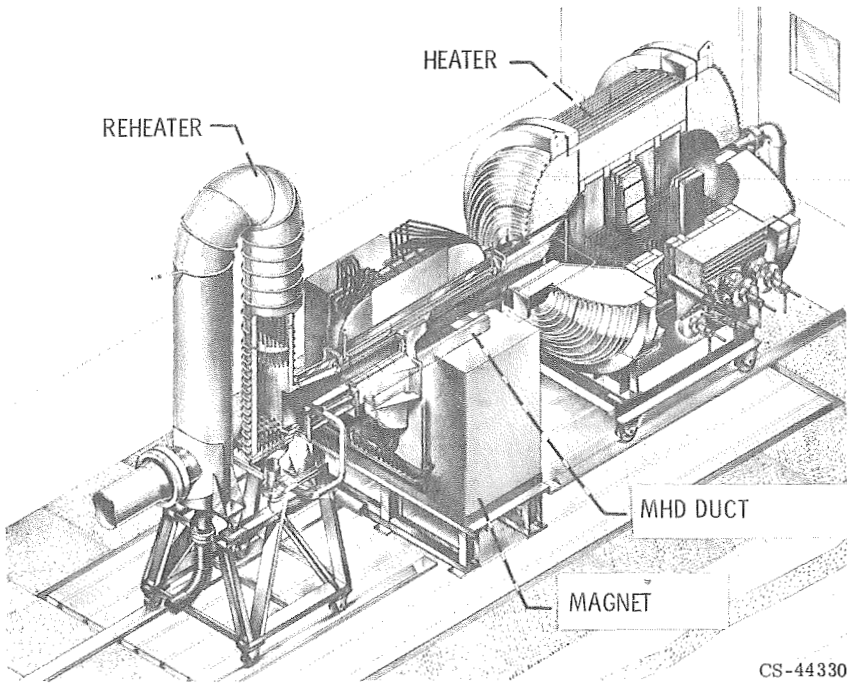
CS-26151

Figure II-2. - Power generator cycle with MHD energy converter.



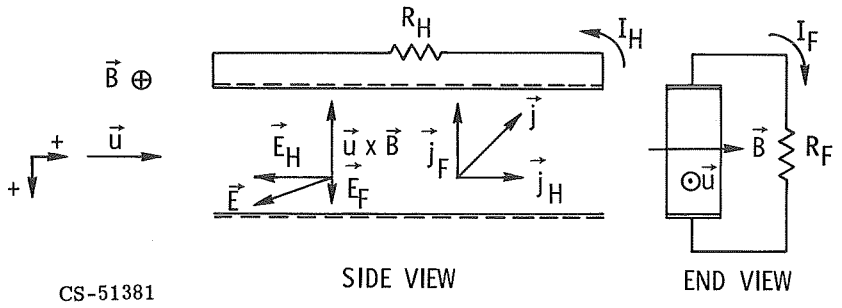
CS-47582

Figure II-3. - 31.3 Megawatts electric combustion-fired MHD generator.



CS-44330

Figure II-4. - MHD generator experiment.



CS-51381

Figure II-5. - MHD generator.

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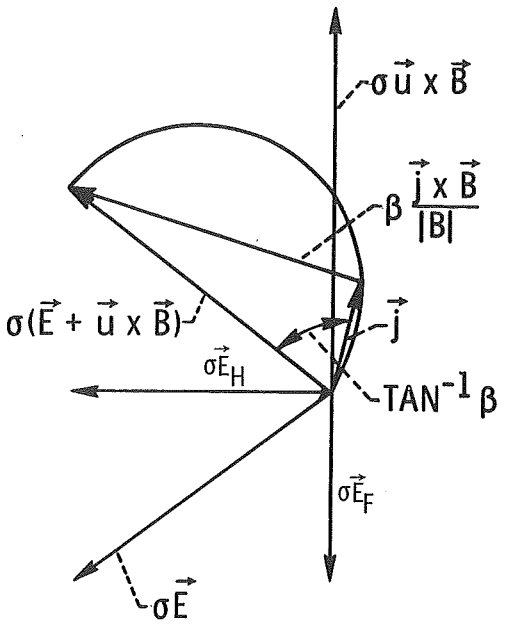


OHM'S LAW

$$\vec{j}+\beta\frac{\vec{j}\times\vec{B}}{|B|}=\sigma(\vec{E}+\vec{u}\times\vec{B})$$

CS-51382

Figure II-6. - Electric field vector diagram ($|\vec{u}\times\vec{B}|>\vec{E}_F$).

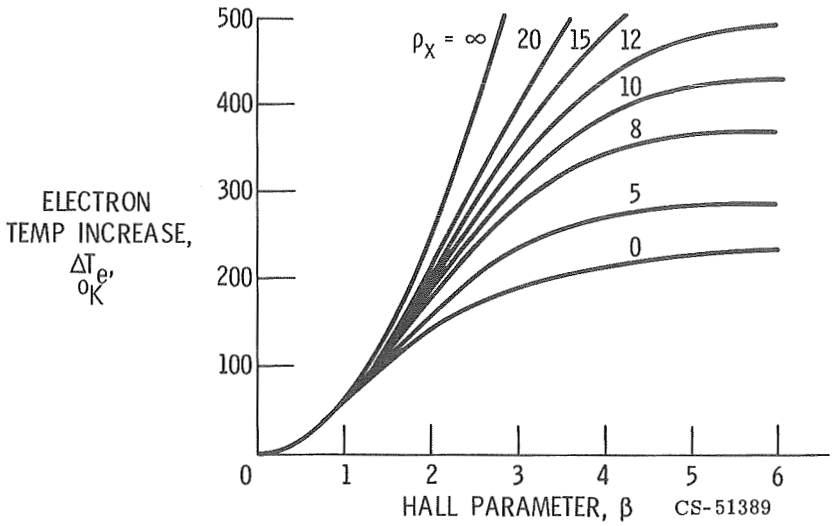


Figure II-7. - Electron temperature increase in Faraday segmented generator. $p_y = 1$; $(\gamma M^2 T/3\delta) = 257.5$ K.

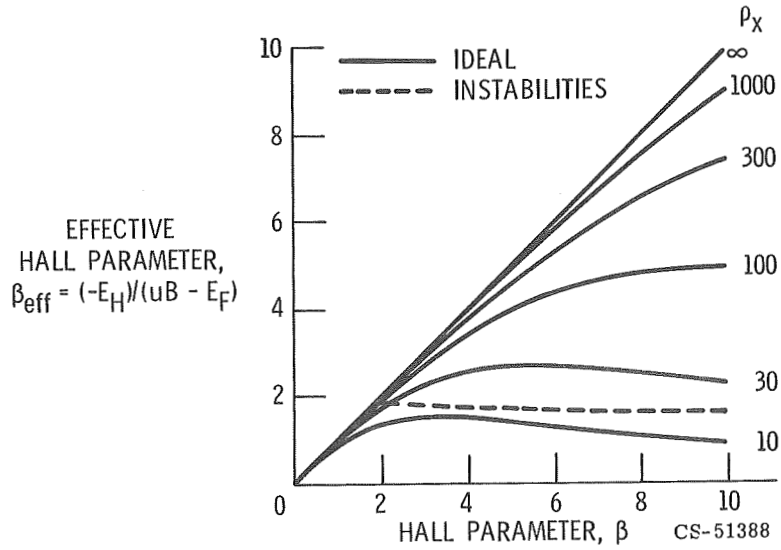


Figure II-8. - Effect of Hall current and instabilities on effective Hall parameter.

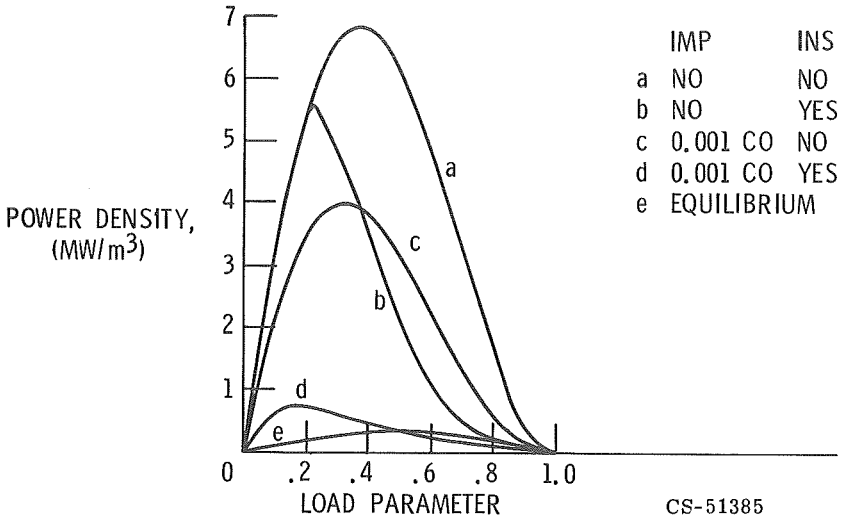


Figure II-9. - MHD generator power density. Mach number, 0.5; T = 2000 K; P = 2×10^5 newtons per square meter.

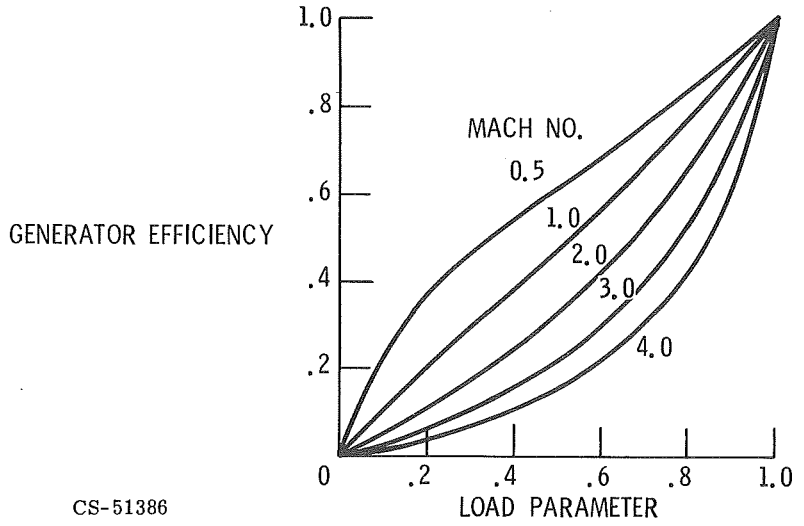


Figure II-10. - MHD generator efficiency. Pressure ratio, 0.5.

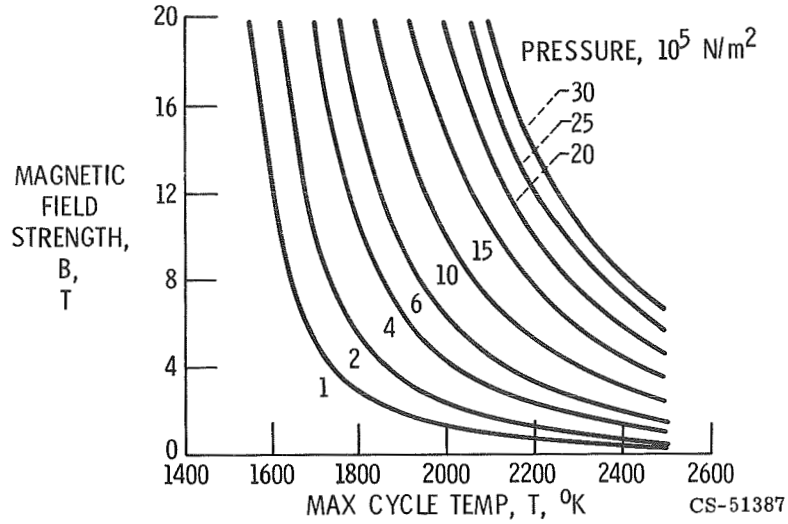


Figure II-11. - Required magnetic field strength for Brayton cycle MHD. Mach number, 2.0; Ne - 0.003 Cs; generator length, 0.5 meter.

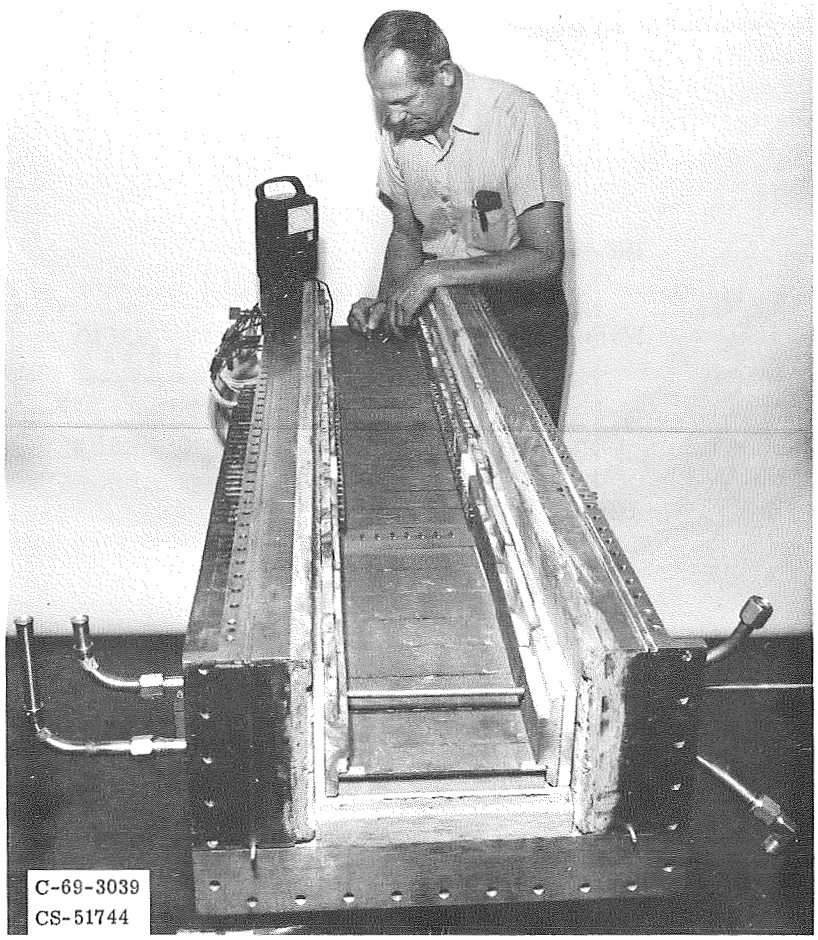
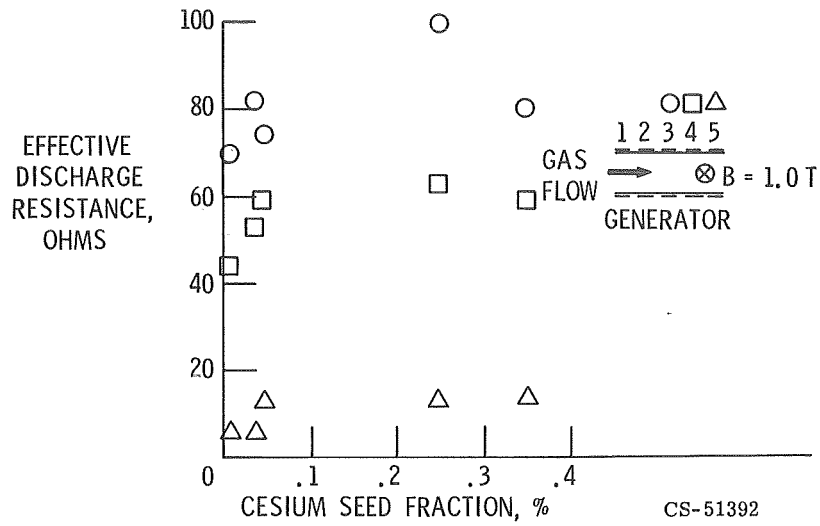
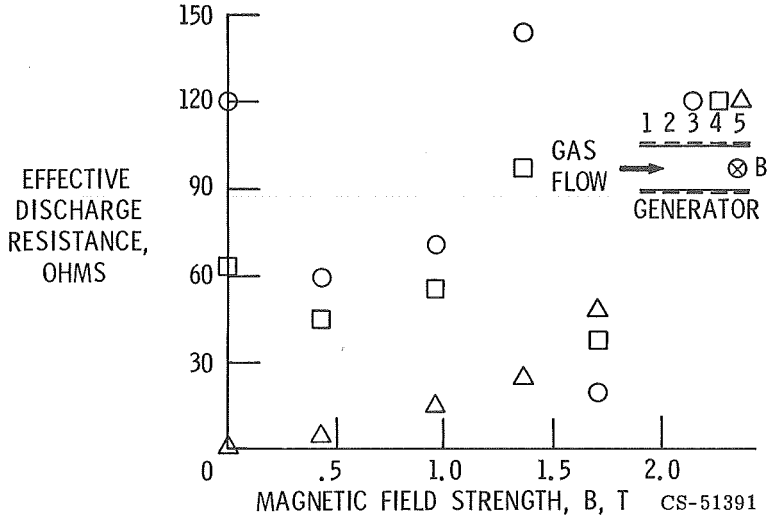


Figure II-12. - MHD generator.



(a) Magnetic field strength, B = 1.0 tesla.



(b) Seed fraction, S = 0.05 percent.

Figure II-13. - Effective discharge resistance for argon seeded with cesium.